Imaging at High Spatial Resolution: Soft X-Ray Microscopy and EUV Lithography

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The Short Wavelength Region of the Electromagnetic Spectrum

- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity
Two Common Soft X-Ray Microscopes

**Full-Field Microscope**

- Best spatial resolution
- Modest spectral resolution
- Shortest exposure time
- Bending magnet radiation
- Higher radiation dose
- Flexible sample environment (wet, cryo, labeled magnetic fields, electric fields, cement, ...)

**Scanning Microscope**

- Least radiation dose
- Good spatial resolution
- Best spectral resolution
- Requires spatially coherent radiation
- Long exposure time
- Flexible sample environment
- Photoemission (restricted magnetic fields), fluorescence imaging
Zone Plates for Soft X-Ray Image Formation

Zone Plate Lens

Soft X-Ray Microscope

Zone Plate Formulae

\[ r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4} \quad (9.9) \]
\[ D = 4N\Delta r \quad (9.13) \]
\[ f = \frac{4N(\Delta r)^2}{\lambda} \quad (9.14) \]
\[ NA = \frac{\lambda}{2\Delta r} \quad (9.15) \]
\[ \text{Res.} = k_1 \frac{\lambda}{NA} = 2k_1\Delta r \quad (9.50) \]
\[ \text{DOF} = \pm \frac{1}{2} \frac{\lambda}{(NA)^2} \quad (9.52) \]
\[ \frac{\Delta \lambda}{\lambda} \leq \frac{1}{N} \quad (9.52) \]

\[ \lambda = 2.5 \text{ nm}, \]
\[ \Delta r = 25 \text{ nm} \]
\[ N = 618 \]
\[ \lambda = 63 \mu \text{m} \]
\[ 0.63 \text{ mm} \]
\[ 0.05 \]
\[ 1.22\Delta r = 30 \text{ nm} \]
\[ 0.8\Delta r = 19 \text{ nm} \]
\[ 1 \mu \text{m} \]
\[ 1/700 \]
Partially Coherent Illumination Permits Improved Spatial Resolution by a Factor Approaching Two

\[ \sigma = \frac{\sin \theta_{\text{illum}}}{\sin \theta} \]
Optical Transfer Properties with Varying Degrees of Partially Coherent Illumination

![Graph showing apparent transfer function vs. spatial frequency (NA/\lambda) for different degrees of partial coherence: \sigma = 0 (coherent), \sigma = 0.3, \sigma = 0.6, and \sigma = \infty (incoherent).]
A Fresnel Zone Plate Lens
Used for X-Ray Microscopy

Courtesy of E. Anderson (LBNL)
The Nanowriter: High Resolution Electron Beam Writing With High Placement Accuracy

Deflection coils

High brightness thermal field emission source and extraction electrodes

Condenser lens, beam defining aperture and transfer lens

Blanking plates and aperture

Final electron focusing lens

50-100 keV electron beam focused to 3-10 nm spot size

Deflection electronics

Pattern generator

System control computer

Thin resist recording layer on a multilevel wafer

Wafer stage (stationary during exposure)

Courtesy of E. Anderson (LBNL)
## Key Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nanowriter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam size</td>
<td>5.0 nm</td>
</tr>
<tr>
<td></td>
<td>2.5 nm (New C3 lens)</td>
</tr>
<tr>
<td>Beam placement</td>
<td>2.5 nm (65 (\mu)m field)</td>
</tr>
<tr>
<td></td>
<td>20 nm (512 (\mu)m field)</td>
</tr>
<tr>
<td>Stitching</td>
<td>20 nm (1 cm field)</td>
</tr>
<tr>
<td>Beam voltage</td>
<td>20-100 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>1 nA at 10 nm</td>
</tr>
<tr>
<td></td>
<td>1.0-0.2 nA at 2.5 nm</td>
</tr>
<tr>
<td></td>
<td>(new C3 lens)</td>
</tr>
<tr>
<td>Speed</td>
<td>25 MHz</td>
</tr>
<tr>
<td>Deflection field</td>
<td>16 bit</td>
</tr>
<tr>
<td>Interferometer</td>
<td>(\lambda/1024)</td>
</tr>
<tr>
<td>Wafer size</td>
<td>8&quot;</td>
</tr>
<tr>
<td>Real time detection and feedback</td>
<td>Backscattered, transmitted and secondary electrons; digital image processing</td>
</tr>
</tbody>
</table>

Courtesy of E. Anderson (LBNL)
Nanofabrication is Critical for High Fidelity, High Aspect Ratio Zone Plates

1. Expose

2. Develop

3. Cryogenic ICP Etch

4. Plate

5. Strip Resist

6. Strip Si₃N₄ and Cr/Au Plating Base

Courtesy of E. Anderson, A. Liddle, W. Chao, D. Olynick, and B. Harteneck (LBNL)
Spectromicroscopy: High Spatial and High Spectral Resolution Studies of Surface and Thin Films

Photoelectron spectrometer
Zone plate focusing lens
Transmission

25 nm elbow test pattern

Scanning Soft X-Ray Microscope
ALS beamline 11.0.2
395 eV; $\lambda/\Delta\lambda = 6000$
240 x 240 pixels
1.2 $\mu$m x 1.2 $\mu$m
2 ms dwell time

Courtesy of Tolek Tyliszczak (Dec. 2003)
Biofilm from Saskatoon River

RESULTS

• Ni, Fe, Mn, Ca, K, O, C elemental map,
  (there was no sign of Cr.)
• Different oxidation states for Fe and Ni

Protein (gray), Ca, K

Different oxidation states (minerals) found for Fe & Ni

Tohru Araki, Adam Hitchcock (McMaster University)
Tolek Tyliszczak, LBNL
Sample from: John Lawrence, George Swerhone (NWRI-Saskatoon), Gary Leppard (NWRI-CCIW)
Beamline Layout for a High Spatial Resolution, High Spectral Resolution, Full Field Microscope

Power in the central radiation cone

\[
P_{\text{cen}} (W) = \begin{cases} 
3 \text{ GeV, 500 mA} \\
\lambda_u = 48 \text{ mm} \\
N = 78 \\
K \leq 4.2 
\end{cases} \]

\[
\frac{\lambda}{\Delta\lambda} = \begin{cases} 
1 & n = 1 \\
78 & n = 3 \\
230 & \text{other values} 
\end{cases}
\]

Photon Energy (eV)
Power Curves for the Stanford EPU

3 GeV, 500 mA
\( \lambda_u = 48 \text{ mm} \)
N = 78
K ≤ 4.2
\( \sigma_h = 420 \text{ \( \mu \)m} \)
\( \sigma_v = 42 \text{ \( \mu \)m} \)
\( \sigma_{h} = 42 \text{ \( \mu \)r} \)
\( \sigma_{v} = 6 \text{ \( \mu \)r} \)
\( \theta_{cen} = 30 \text{ \( \mu \)r} \)

\[ \frac{\lambda}{\Delta \lambda} = 3000 \]
\[ \eta = 0.84\% \]
Photon Flux Curves for the Stanford EPU

3 GeV, 500 mA
\( \lambda_u = 48 \text{ mm} \)
\( N = 78 \)
\( K \leq 4.2 \)
\( \sigma_h = 420 \mu m \)
\( \sigma_v = 42 \mu m \)
\( \sigma_h' = 42 \mu r \)
\( \sigma_v' = 6 \mu r \)
\( \theta_{cen} = 30 \mu r \)

\[ \frac{\lambda}{\Delta \lambda} = 3000 \]
\[ \eta = 0.84\% \]
A Novel Illuminator is Required

Scanning optics modify phase space, transforming elliptical spatial distribution to circular, and increasing the angular illumination to provide the desired degree of partial coherence. Based on experience with EUV lithographic imaging at ALS Beamline 12.0, P. Naulleau and P. Denham (CXRO), SRI-2003, p. 792.

## Exposure Time for a Full Field, High Spatial and High Spatial Resolution, Soft X-Ray Microscope on an EPU at Stanford

Photon flux in central radiation cone / 6.43E+16 #/sec at 500 eV ($\lambda = 2.5$ nm, $\lambda/\Delta\lambda = 78$)

Spectral filter to $\lambda/\Delta\lambda = 3,000 / 1.776E+15$

Beamline efficiency (0.84%) (7 mirrors plus 1 grating @ 10%) / 1.45E+13

### CONDENSER

<table>
<thead>
<tr>
<th>type</th>
<th>ZP</th>
</tr>
</thead>
<tbody>
<tr>
<td>collection NA</td>
<td>rad</td>
</tr>
<tr>
<td>collection solid angle</td>
<td>8.26E-03 sr</td>
</tr>
<tr>
<td>magnification</td>
<td>5</td>
</tr>
<tr>
<td>illumination NA</td>
<td>0.0413 rad</td>
</tr>
<tr>
<td>illumination solid angle</td>
<td>sr</td>
</tr>
<tr>
<td>sigma</td>
<td>6.70E-01</td>
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<tr>
<td>KZP collection percentage</td>
<td>100%</td>
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<tr>
<td>collected flux</td>
<td>1.45E+13 #/sec at 2.5nm</td>
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<tr>
<td>efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>post-condenser flux</td>
<td>1.45E+12 #/sec at 2.5nm</td>
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</table>

### SAMPLE

<table>
<thead>
<tr>
<th>illumination area (ellipse)</th>
<th>20 x 20 µm^2</th>
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<tbody>
<tr>
<td>sample size</td>
<td>10 x 10 µm^2</td>
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<tr>
<td>illumination efficiency</td>
<td>0.25</td>
</tr>
<tr>
<td>efficiency</td>
<td>50%</td>
</tr>
<tr>
<td>flux after sample</td>
<td>1.81E+11 #/sec at 2.5nm</td>
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</tbody>
</table>

### MZP

<table>
<thead>
<tr>
<th>MZP D</th>
<th>63 µm</th>
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<tbody>
<tr>
<td>MZP $\Delta r$</td>
<td>20 nm</td>
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<tr>
<td>MZP f</td>
<td>525 µm</td>
</tr>
<tr>
<td>MZP NA</td>
<td>0.06</td>
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<tr>
<td>MZP efficiency</td>
<td>8%</td>
</tr>
<tr>
<td>flux after MZP</td>
<td>1.45E+10</td>
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</table>

### CCD

<table>
<thead>
<tr>
<th>CCD pixel size</th>
<th>12.5 µm x 12.5 µm</th>
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<tbody>
<tr>
<td>CCD pixels</td>
<td>(2048)^2</td>
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<tr>
<td>CCD dimension</td>
<td>1&quot; x 1&quot;</td>
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<tr>
<td>CCD efficiency</td>
<td>80%</td>
</tr>
<tr>
<td>total flux onto CCD</td>
<td>1.16E+10 #/sec at 2.5nm</td>
</tr>
<tr>
<td>CCD counts per pixel per sec</td>
<td>2.77E+03 #/sec at 2.5nm</td>
</tr>
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</table>

**0.36 sec exposure time**

*for full field microscope

$\lambda = 2.5$ nm, $\lambda/\Delta\lambda = 3000$

Spatial resolution ~20 nm
The XM-1 Soft X-Ray Microscope at the Advanced Light Source (ALS)

- High spatial resolution (20 nm)
- Modest spectral resolution ($E/\Delta E \sim 700$)
- Thick, hydrated samples (10 µm)
- Short exposure time (~1 second)
- Well engineered, pre-focused
- Mutually indexed visible and x-ray microscopes
- High throughput (hundreds of samples per day)
- Large image fields by tiling
- Easy access, user friendly
- Cryotomography

$E = 250 - 1.8$ keV
$\lambda = 0.7$ nm - 5 nm
High Resolution Zone-Plate Microscope XM-1 at the ALS

- Well engineered
- Sample indexing
- Tiling for larger field of view
- Pre-focused
- High sample throughput
- Illumination important
- Phase contrast

![Diagram of the High Resolution Zone-Plate Microscope XM-1 at the ALS](image)

- ALS Bending Magnet
- Plane mirror
- Condenser zone plate
- Pinhole
- Mutual Indexing System with kinematic mounts
- Sample stage
- Micro zone plate
- Soft x-ray sensitive CCD
- Visible light microscope
Test Pattern for Nanometer Soft X-Ray Imaging

Courtesy of E. Anderson, D. Olynick, B. Harteneck, E. Veklerov
Soft X-Ray Microscopy at the ALS: 20 nm Spatial Resolution

Δr = 25 nm, D = 63 µm, N = 618 zones

E. Anderson (LBNL)

24 nm Cr/Si lines, 1:1

W. Chao (UCB & LBNL)

Multilayer Mirror Coatings Can Be Thinned and Used As Sub-20 nm Test Patterns

High quality test patterns can be fabricated with sections as thin as 5 nm.

SEM Micrograph of Cr/Si test pattern

Courtesy of W. Chao (UCB & CXRO/LBNL)
Near Diffraction Limited Soft X-Ray Microscopy: 20 nm Spatial Resolution at 2.07 nm Wavelength

W. Chao et al.,

(Courtesy of Weilun Chao, UC Berkeley and CXRO/LBNL)
Near Diffraction Limited Soft X-Ray Microscopy: 20 nm Spatial Resolution at 2.07 nm Wavelength

W. Chao et al.,
New Overlay Nanofabrication Technique for Narrower Outer Zones

\[ \Delta r = 15 \text{ nm} \]
\[ \Delta t = 90 \text{ nm} \]
Overlay \( \approx 2 \text{ nm accuracy} \)

Courtesy of J.A. Liddle, E.H. Anderson, B. Harteneck and W. Chao, LBNL
New Results Using Overlay Nanofabrication: Outer Zone Width of 15 nm

- Zone plate lenses made using a new, e-beam based nanofabrication technique have extended outer zones from 25 nm to 15 nm.
- The new lenses work as expected, resolving fine patterns not seen previously.
- Shorter depth of focus ($\lambda/NA^2$) opens the opportunity for soft x-ray “optical sectioning” of biological material.

New zone plate lens with 15 nm outer zone width

Soft x-ray image of 15 nm Cr/Si lines & spaces

Courtesy of W. Chao, A. Liddle, E. Anderson, and B. Harteneck (CXRO/LBNL)
Applications of Soft X-Ray Microscopy

Magnetic Recording Materials

- FeTbCo Multilayer with AL Capping Layer
- 100 nm lines & spaces
- Fe L₃ @ 707.5 eV

Cryo Microscopy for the Life Sciences

- Cryo X-Ray Microscopy of 3T3 Fibroblast Cells
- Protein Labeled Microtubule Network

Courtesy of P. Fischer (Max Planck) and G. Denbeaux (CXRO/LBNL)

Courtesy of C. Larabell (UCSF) and W. Meyer-Ilse (CXRO/LBNL)
The Water Window for Biological X-Ray Microscopy

![Graph showing the absorption length (µm) vs. photon energy (eV) for Water, Protein, Carbon, Oxygen, Nitrogen, and Sulfur.]

- **Typical protein:**
  - Carbon 52.5%
  - Oxygen 22.5%
  - Nitrogen 16.5%
  - Hydrogen 7.0%
  - Sulfur 1.5%
Fast Freeze Cryo Fixation Strongly Mitigates Radiation Dose Effects

Helium passes through LN, is cooled, and directed onto sample windows.

Fast Freeze Cryo Fixation Strongly Mitigates Radiation Dose Effects

\[ \Delta T = \frac{50°C}{16 \text{ ms}} \]

W. Meyer-Ilse, G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)
Cryo x-ray microscopy of 3T3 fibroblast cells

C. Larabell, D. Yager, D. Hamamoto, M. Bissell, T. Shin (LBNL Life Sciences Division)
W. Meyer-Ilse, G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)
Bending Magnet Radiation Used With a Soft X-Ray Microscope to Form a High Resolution Image of a Whole, Hydrated Mouse Epithelial Cell

$\hbar \omega = 520 \text{ eV}$

32 $\mu$m x 32 $\mu$m

Ag enhanced Au labeling of the microtubule network, color coded blue.

Cell nucleus and nucleoli, moderately absorbing, coded orange.

Less absorbing aqueous regions coded black.

W. Meyer-Ilse et al.
J. Microsc. 201, 395 (2001)

Courtesy of C. Larabell and W. Meyer-Ilse (LBNL)
Bio-Nanotomography for 3D Imaging of Cells

Nanotomography of Cryogenic Fixed Cells

![Diagram of nanotomography setup](image)

\[ \lambda = 2.5 \text{ nm} \]

Soft X-Ray Nanotomography of a Yeast Cell

![Image of yeast cell](image)

Courtesy of G. Schneider (BESSY)  

Courtesy of C. Larabell (UCSF & LBNL) and M. LeGros (LBNL)
Bio-Nanotomography for 3D Imaging of Cells

Nanotomography of Cryogenic Fixed Cells

Soft X-Ray Nanotomography of a Yeast Cell

\[ \lambda = 2.5 \text{ nm} \]

Magnetic X-Ray Microscopy

- High spatial resolution in transmission
- Bulk sensitive (thin films)
- Complements surface sensitive PEEM
- Good elemental sensitivity
- Good spin-orbit sensitivity
- Allows applied magnetic field
- Insensitive to capping layers
- In-plane and out-of-plane measurements

Courtesy of P. Fischer, (MPI, Stuttgart) and G. Denbeaux (CXRO/LBNL)
Magnetic Domains Imaged at Different Photons Energies

FeGd Multilayer

Contrast reversal

\( \hbar \omega = 704 \text{ eV} \)
below Fe L-edges

\( \hbar \omega = 707.5 \text{ eV} \)
Fe L\(_3\)-edge

\( \hbar \omega = 720.5 \text{ eV} \)
Fe L\(_2\)-edge

P. Fischer, T. Eimueller, M. Koehler (U. Wuerzberg)
S. Tsunashima (U. Nagoya) and N. Tagaki (Sanyo)
G. Denbeaux, L. Johnson, A. Pearson (CXRO-LBNL)
Imaging of Ultrafast Spin Dynamics with Magnetic Soft X-Ray Transmission Microscopy

• stroboscopic pump-and-probe technique at variable delay times (Δt)
• high lateral resolution (<20nm) provided by Fresnel zone plates
• high temporal resolution given by SR pulse width (<100ps)
• inherent chemical sensitivity provided by XMCD magnetic contrast

Sample: 4x4μm² PY element

P. Fischer et al., MPI-MF, Stuttgart, Germany (now LBNL)
Electromigration in Latest Technology Computer Chips with Cu vias Connecting Multilevel Metallization Layers

SEM micrograph

X-ray micrograph imaged at 1.8 keV

HVTEM (0.8 MeV electrons)

TXM (1.8 keV photons)

Cu interconnect

Cu via

Wafer

1 μm

X-rays

Via with metal line as dark shadow

thickness approx. 1 - 2 μm

Void

Grain boundaries

200 nm

High current density

Courtesy of Gerd Schneider (BESSY)

G. Denbeaux, E. Anderson, A. Pearson and B. Bates (CXRO)
M. Meyer and E. Zschech (AMD Saxony Manufacturing GmbH) / E. Stach (NCEM / LBNL)
Extreme Ultraviolet (EUV) Lithography Based on Multilayer Coated Optics

Reflective mask

Absorber pattern

\[ \lambda = 13 \text{ nm} \]

Multilayer mirror

4:1 reduction optics, aspheric, multilayer coated

6.7 nm period

Mo

Si

Wafer to record 50 nm or smaller features, over cm\(^2\) dimensions
# High Reflectivity, Thermally and Environmentally Robust Multilayers Coatings for High Throughput EUV Lithography

![Diagram of multilayers coating with wavelengths and thicknesses](image)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ru</td>
<td>1.70</td>
</tr>
<tr>
<td>Si</td>
<td>4.14</td>
</tr>
<tr>
<td>Mo</td>
<td>2.09</td>
</tr>
<tr>
<td>B₄C</td>
<td>0.25</td>
</tr>
<tr>
<td>B₄C</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Substrate

- λ = 13.4 nm

Mo/B₄C/Si
- 70% at 13.5 nm
- FWHM = 0.55 nm
- 50 bilayers

Courtesy of Saša Bajt (LLNL)
Reflective Mask for EUV Lithography

Absorber pattern

Buffer layer

Capping layer

Multilayer Coating

Substrate: Low thermal expansion material (LTEM) (6" square x 1/4" thick)

<table>
<thead>
<tr>
<th>Attribute</th>
<th>TaN</th>
<th>Cr</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD control</td>
<td>✓</td>
<td></td>
<td>TaN has smaller RIE CD bias</td>
</tr>
<tr>
<td>Cleaning</td>
<td></td>
<td></td>
<td>Both resistant to standard cleans</td>
</tr>
<tr>
<td>Emissivity</td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Inspection contrast</td>
<td>✓</td>
<td></td>
<td>TaN has higher contrast</td>
</tr>
<tr>
<td>Repair selectivity</td>
<td></td>
<td></td>
<td>Both need small improvement</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>✓</td>
<td></td>
<td>TaN can be 8 nm thinner than Cr</td>
</tr>
</tbody>
</table>

Typically

Mo/Si multilayer (d = 6.7 nm) with 30 nm SiO₂ capping layer
Cr or TaN absorber (~70 nm) with 50 nm Ru Buffer layer
LTEM substrate (Ti-doped fused silica) ULE (Corning), or Zerodur (Schott)
The Engineering Test Stand (ETS): A Pre-Manufacturing EUV Stepper

Mask stage

Projection optics

Wafer stage

Collection optic

EUV Plasma source

Condenser optics
The Engineering Test Stand (ETS)

Courtesy of
Bill Replogle,
Sandia National Laboratories
EUV Lithography Will Use a Step and Scan Ring Field System
ETS Optics Meet Tight Specifications

Condenser optic

Projection optic

Courtesy of D. Sweeney (LLNL)
High Reflectivity, Thermally and Environmentally Robust Multilayer Coatings for High Throughput EUV Lithography

Ru capping layer

Mo
Si
B₄C
Si
Mo
Si
Mo

Substrate

λ = 13.4 nm
Ru (1.70 nm)
Si (4.14 nm)
B₄C (0.25 nm)
Mo (2.09 nm)
B₄C (0.40 nm)

d = 6.88 nm
Γ = 0.34

Mo/B₄C/Si
70% at 13.5 nm
FWHM = 0.55 nm
50 bilayers

Courtesy of Saša Bajt (LLNL)
DC Magnetron Sputtering Is Used to Deposit Multilayer Coatings Onto Optical Substrates

Substrates mounted on a rotating platter are swept across each sputter source sequentially to form the multilayer. Modulating the platter velocity provides precision control of radial thickness distribution and absolute film thickness. The substrate is also spun fast about its own axis for azimuthal uniformity.
Multilayer Reflectivity and Uniformity

Courtesy of E. Gullikson and J. Underwood, Lawrence Berkeley National Laboratory.
High Accuracy EUV Metrology for Multilayer Coated Optics

Multilayer Reflectivity and Uniformity

Wavelength accuracy to $10^{-4}$
Reflectivity to $10^{-3}$
EUV scattering to $10^{-9}$

Calibration lines
- Xe 4d$_{5/2} - 6p$ 19.0423 nm
- Kr 3d$_{5/2} - 5p$ 13.5948 nm
- Ar 2p$_{3/2} - 4s$ 5.0736 nm
- CO 1s $- \pi^*$ 4.3140 nm
- N$_2$ 1s $- \pi^*$ 3.0911 nm

Courtesy of E. Gullikson and J. Underwood (LBNL)
Systematic d-space variations suggest path to further improvements.

**ETS M1 Mirror**
- Added figure error = 0.032 nm rms
- $\Delta d/d = 1/8800$ ($\lambda/420$)

**ETS M2 Mirror**
- Added figure error = 0.037 nm rms
- $\Delta d/d = 1/7600$ ($\lambda/360$)

**ETS M3 Mirror**
- Added figure error = 0.040 nm rms
- $\Delta d/d = 1/6900$ ($\lambda/340$)

**ETS M4 Mirror**
- Added figure error = 0.015 nm rms
- $\Delta d/d = 1/19,000$ ($\lambda/890$)

Courtesy of R. Souffli and E. Spiller, LLNL.
ETS Mirror M3 Was Successfully Coated While Preserving the Surface Figure

Uniform direction

Graded direction

Radial Position (mm)

Normalized film thickness

-20 -10 0 10 20

0.990 0.995 1.000 1.005

Uniform direction

Graded direction
Figure and Finish Low, Mid, and High Spatial Frequency Variations from the Perfect Optical Surface

Mid spatial frequency surface variations contribute to flare, small angle scattering that reduces contrast between nearby features.

Low spatial frequency substrate errors are associated with aberrations, blurred features.

High spatial frequency roughness scatters radiation to large angles, reducing power throughput to the image (wafer).

Note: Multilayer coatings must be sufficiently uniform that they do not contribute significantly to the top surface error budget. For an rms d-space variation $\Delta d$, the coating thickness variation $\Delta h = N \Delta d < \lambda_{\text{euv}}/500$. 
Spatially Coherent Radiation for At-Wavelength EUV Interferometry

$\lambda = 11.2$ nm

$\lambda = 13.4$ nm

1 $\mu$m$^D$ pinhole

25 mm wide CCD at 410 mm
At-Wavelength EUV Interferometry

Wavefront Accuracy to $\lambda_{euv}/300$

Null test interferogram

Reference wavefront $\sigma = 0.044$ nm rms = $\lambda_{euv}/300$

EUV Interferometry of ETS Optics

K-B pre-focusing mirrors

From undulator beamline

Object stage Pinhole array

Grating stage

Planar Bearing stage

Image stage Pinhole array

EUV CCD

Courtesy of K. Goldberg, P. Naulleau and P. Batson (LBNL) and J. Bokor (UCB/LLNL)
EUV Interferometry of the ETS Projection Optics

Object and image plane pinhole stages rotate with the projection optics to cover the field of view.

Courtesy of K. Goldberg, P. Naulleau and P. Batson (LBNL) and J. Bokor (UCB/LLNL)

Stanford-Berkeley Summer School 2005/David Attwood
EUV Lithography at the Advanced Light Source in Berkeley

Courtesy of P. Naulleau, S. Rekawa, and E. Anderson (LBNL)
At-Wavelength Interferometry of ETS Set 2 Optics

- Quantitative agreement with visible light interferometry to 0.25 nm rms
- Best field points chosen for static imaging

Courtesy of K. Goldberg, P. Naulleau, J. Bokor, et al. (LBNL)
EUV-Wavelength Aberration Breakdown for the ETS Set-2 Optics

$|\text{Astigmatism}| = \sqrt{\text{Astigmatism}^2 + \text{Astigmatism}^2}$

$|\text{Comal}| = \sqrt{\text{Comal}^2 + \text{Comal}^2}$

$|\text{Spherical Aberration}| = \sqrt{\text{Spherical Aberration}^2}$

$|\text{Trifoill}| = \sqrt{\text{Trifoill}^2 + \text{Trifoill}^2}$
Visible and EUV Wavefront Comparison by the Numbers

<table>
<thead>
<tr>
<th></th>
<th>Visible-light</th>
<th>EUV</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FP 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(37-term) RMS</td>
<td>1.236</td>
<td>1.572</td>
<td>0.394</td>
</tr>
<tr>
<td>RMS Astigmatism</td>
<td>0.925</td>
<td>1.291</td>
<td>0.367</td>
</tr>
<tr>
<td>RMS Coma</td>
<td>0.256</td>
<td>0.236</td>
<td>0.083</td>
</tr>
<tr>
<td>RMS Sph. Ab.</td>
<td>0.104</td>
<td>0.146</td>
<td>0.042</td>
</tr>
<tr>
<td>RMS Trifoil</td>
<td>0.432</td>
<td>0.460</td>
<td>0.031</td>
</tr>
<tr>
<td><strong>FP 23</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(37-term) RMS</td>
<td>0.648</td>
<td>0.745</td>
<td>0.271</td>
</tr>
<tr>
<td>RMS Astigmatism</td>
<td>0.116</td>
<td>0.221</td>
<td>0.216</td>
</tr>
<tr>
<td>RMS Coma</td>
<td>0.183</td>
<td>0.094</td>
<td>0.100</td>
</tr>
<tr>
<td>RMS Sph. Ab.</td>
<td>0.212</td>
<td>0.267</td>
<td>0.055</td>
</tr>
<tr>
<td>RMS Trifoil</td>
<td>0.306</td>
<td>0.339</td>
<td>0.047</td>
</tr>
</tbody>
</table>

Courtesy of K. Goldberg (LBNL)
EUV Static Exposures Demonstrated to 39 nm Linewidth

39 nm Isolated Line

ETS Set 2 optics
Static images at ALS
13.5 nm
$\sigma = 0.7$
DOF = ± 1/2 μm
EUV 2D resist, 120 nm thick
6.2 mj/cm$^2$, 4-6 nm LER

Coded as 80 nm (1:1) narrowed by exposure bias (x1.4)

Courtesy of P. Naulleau (LBNL)
A 0.30 NA Micro-Exposure Tool (MET) has been Fabricated by Zeiss and LLNL

**MET**
- NA = 0.30
- 13.4 nm
- 5X
- 200 X 600 μm field

**Courtesy of J. Taylor (LLNL)**
25 nm Pinhole Fabrication

Cr 5nm/Au 12 nm
Plating Base

HSQ Resist

Expose &
develop

HSQ
Ni Plate

HSQ
strip in

HF
Dry Etch SiN

SEM of
coded 50 nm
pinhole with
HSQ mold
inside

300 nm

TEM of
coded 25 nm
pinholes on
500 nm pitch

50 nm

Courtesy of J. Alex Liddle, Deirdre Olynick and Erik Anderson (LBNL)
Measured Pinhole Performance

- Pinholes show a consistent 5 nm bias
- Aspect ratio of pinholes is limited by mechanical stability of resist
- 20 nm coded pinholes produce almost 50% diffracted power at an NA of 0.3

Courtesy of E. Gullikson, K. Goldberg, J.A. Liddle, D. Olynick, E. Anderson, (LBNL)
MET At-Wavelength Interferometry and Alignment Preparation for Static Microfield Imaging

Alignment in progress
September 3, 2003
central field point

- astig  0.1 nm
- coma  0.3 nm
- sph ab  0.4 nm
- trifoil  0.2 nm
- h-o s.  0.4 nm
- RMS  0.8 nm

λ/17

aberrations may be reduced in final alignment

2 mirrors
0.3 NA, 5x
13.5 nm

200 x 600 μm
field of view

- Visible-light alignment at Livermore
- EUV interferometry at Berkeley includes PS/PDI and shearing at 9 points across the field of view and in z.
- Higher-order spherical aberration dominates the wavefront
- A large part of the higher-order spherical is contained in Z35 and Z36. Higher-order spherical magnitude depends strongly on NA.

Courtesy of K. Goldberg and P. Naulleau (LBNL)
Rohm and Haas MET 1K Resist Shows 10-15 nm Resolution Improvement Over EUV 2D

Processing Conditions:
- Thickness 125-nm
- PEB 130 °C 90 Sec
- Develop 45 Sec
- $E_{\text{size}}$ 50-nm 21 mJ/cm²

Courtesy of P. Naulleau (LBNL), R. Brainard & T. Koehler (Rohm & Haas)

SPIE Microlithography March, 2005,

Stanford-Berkeley Summer School 2005/David Attwood
MET 1K Resist Shows Modulation Down to the 25-nm Level

Courtesy of Patrick Naulleau (LBNL)
SPIE Microlithography March, 2005,
MS-13 tool chamber – subsystem testing

Courtesy of Malcolm Gower (Oxford, UK)
Intel EUV MET Installation

16 crates
17+ tons
15 pumps
All for . . . .

Jeanette Roberts  SPIE  March 1, 2005
Imaging Performance

0.3 NA
0.55/0.36 σ
8 mJ/cm²

45 nm 1/2 pitch
160 nm DOF

30 nm isolated line
90 nm thick
80 nm DOF

Jeanette Roberts  SPIE  March 1, 2005
MS-13 EUV Microstepper - at SEMATECH North, Albany, New York, USA

Courtesy of Malcolm Gower, Oxford, UK
## International Technology Roadmap for Semiconductors*

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Technology Generation</td>
<td>130 nm</td>
<td>90 nm</td>
<td>65 nm</td>
<td>45 nm</td>
<td>32 nm</td>
<td>23 nm</td>
</tr>
<tr>
<td>(Dense lines, printed in resist)</td>
<td>[65 nm]</td>
<td>[37 nm]</td>
<td>[25 nm]</td>
<td>[18 nm]</td>
<td>[13 nm]</td>
<td>[9 nm]</td>
</tr>
<tr>
<td>Isolated Lines (in resist)</td>
<td>90 nm</td>
<td>53 nm</td>
<td>35 nm</td>
<td>25 nm</td>
<td>18 nm</td>
<td>13 nm</td>
</tr>
<tr>
<td>[Physical gate, post-etch]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chip Frequency</td>
<td>1.7 GHz</td>
<td>4.0 GHz</td>
<td>6.8 GHz</td>
<td>12 GHz</td>
<td>19 GHz</td>
<td>29 GHz</td>
</tr>
<tr>
<td>Transistors per chip (HV)</td>
<td>100 M</td>
<td>190 M</td>
<td>390 M</td>
<td>780 M</td>
<td>1.5 B</td>
<td>3.1 B</td>
</tr>
<tr>
<td>(3 × for HP ; 5 × for ASICs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRAM Memory (bits)</td>
<td>510 M</td>
<td>1.1 G</td>
<td>4.3 G</td>
<td>8.6 G</td>
<td>34 G</td>
<td>69 G</td>
</tr>
<tr>
<td>Gate CD Control</td>
<td>5 nm</td>
<td>3 nm</td>
<td>2 nm</td>
<td>1.5 nm</td>
<td>1.1 nm</td>
<td>0.7 nm</td>
</tr>
<tr>
<td>(3σ, post-etch)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field Size (mm × mm)</td>
<td>25 × 32</td>
<td>25 × 32</td>
<td>22 × 26</td>
<td>22 × 26</td>
<td>22 × 26</td>
<td>22 × 26</td>
</tr>
<tr>
<td>Chip Size (mm)</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>(2.2 × for HP ; to 4 × for ASIC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Water Size (diameter)</td>
<td>300 mm</td>
<td>300 mm</td>
<td>300 mm</td>
<td>450 mm</td>
<td>450 mm</td>
<td>450 mm</td>
</tr>
</tbody>
</table>

*Semiconductor Industry Association (SIA), December 2001.

*Possible 2-year cycle.
EUV Source Candidates for Clean, Collectable 13-14 nm Wavelength Radiation

Laser Produced Plasma Source

Electronic Discharge Plasma Source

Large solid angle, EUV collection optic, \( \Delta \Omega = 0.6 \) (2\( \pi \))

High voltage

\( \lambda = 1.06 \, \mu m \)

(from high average power, diode pumped, Nd laser. \( P = 10 \, kW, 10 \, kHz \))

Hot (~60 eV), EUV emitting plasma, 1-3% conversion to in-band EUV, 2\( \pi \) steradians

Liquid jet or droplets (Xe, other)

Nozzle

Courtesy of Neil Fornaciari and Glenn Kubiak (Sandia)
Critical Issues for EUV

- 120W compact EUV Source
- EUV source debris mitigation
- Sensitive (5m/cm²) EUV resist with 15 nm resolution and low LER
- Defect free mask
- Environmental controls
Lectures Available Over the Web Free

www.coe.berkeley.edu/AST/sxreuv

AST 210 / EECS 213

(offered Fall 2005,
starts Aug. 30, 2 pm PDT,
live over internet plus archived)